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# Game-theoretic analysis for an emission-dependent supply chain in a ‘cap-and-trade’ system

**S. Du · F. Ma · Z. Fu · L. Zhu · J. Zhang**

**Abstract** The paper focuses on the impact of emission ‘cap-and-trade’ mechanism in a so-called emission-dependent supply chain with the emission permit supplier and the emission-dependent firm. In the cap-and-trade system, emission permit becomes one of key factors of production for emission-dependent firms. Two major sources of emission permits are considered—emission cap/quota imposed by the government, and permits purchased via emission trading. If the quota is insufficient to satisfy the target production, extra permits should be purchased via trading. In this case, the traditional non-profit green organizations may be endowed with the role of emission permit suppliers. Thus, the introduction of market mechanism injects new life into environment protection. In the context of newsvendor, the paper investigates the behavior and decision-making of each member in the emission-dependent supply chain. A game-theoretical analytical model is proposed and the unique Nash equilibrium is derived. In their own self-interest, the emission permit supplier and the emission-dependent firm make their optimal decisions on permits pricing and production quantity respectively. Players’ bargaining power in the game is affected by several exogenous factors, such as the governmental environment policy, the market risk, etc. Several valuable managerial insights on bargaining power affected by external factors (such as environmental policies, market risks, etc.) are further concluded.

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## 1 Introduction

In company with the advance of industrial modernization, massive increase in harmful emissions leads to higher probability of natural disasters and human diseases. As a typical example, carbon emission is scientifically believed to be the principal cause of global warming. In consideration of harmfulness of emission, many governments begin to take note of the importance and urgency of emission reduction, and propose some feasible measures to reduce the risk of climate change, in order to maintain the sustainability of human and social development. Through the joint efforts of the governments around the world, a series of worldwide summits with carbon emission as a central issue have been held. A series of legal covenants have been reached (or can be expected) after long and arduous negotiations. United Nations Framework Convention on Climate Change (UNFCCC) is the first international covenant to cope with the problem of global climate change, which provides obligations and compliance procedures on greenhouse gas emission reduction for developed and developing countries. Kyoto Protocol, as the deepening of UNFCCC, set a “cap and trade” system with both regulation and market. It firstly set emission limits at the national level for the developed countries, and has universal legally binding; and the international emissions trading (IET) mechanisms have been proposed. According to the mechanism, emissions permit is regarded as resources commodity, which can be freely traded through emissions trading market. In 2007, the resolution of “Bali Roadmap” was formally adopted, which seeks a feasible solution to global warming problem through international cooperation under the principle of “common but differentiated responsibilities”. According to Bali Roadmap, the Copenhagen Summit, which was held in 2009, had been expected to reach a post-2012 framework for climate change mitigation, but fell through eventually. The 16th United Nations Climate Change Conference, which achieved the Cancun Agreement, was regarded to have saved the UN climate process, but left a lot to do in the forthcoming Durban Climate Summit in 2011. Despite the fact that the negotiations are ongoing, international emissions trading is widely seen as an indispensable policy pillar of climate change mitigation and will eventually constitute a key building block of future international climate policy (Stern 2008).

Although these caps are national-level commitments, in practice most economies will devolve their emissions targets to individual industrial entities, especially to so-called *emission-dependent firms* in this paper, such as an energy enterprise, power plant, chemical plant or paper factory. The governments constitute emission trading policy and impose emission quotas to domestic firms. In this case, emission permits can be seen as a kind of necessary asset for production, which will significantly impact the emission-dependent firms on production-related decision-makings. Emission-dependent firms should be self-regulated according to the allocated quotas. Those who need more emission have to purchase emission permits from other firms or green organizations (such as Afforestation Promotion Organizations and Environmental Protection Organizations) through emission trading, otherwise, they will be subject to legal sanction. Comparing with the inflexible reward-penalty system of government, ‘cap-and-trade’ mechanism will be more efficient and effective, implementation is made easier, and significant saving in public resources can be achieved. Additionally, it can inject vitality to environmental protection in consideration that the traditionally non-profit green organizations have opportunity to be endowed with the role of producers of emission permits and earn profits by selling their ‘product’. Therefore, they need not solely depend on the financial support from government or social donations. Therefore, a new type of supply chain with emission permit supplier and emission-dependent firm, which is called as *emission-dependent supply chain* in this paper, comes into notice.

In this paper, a typical two-stage emission-dependent supply chain system with one single emission-dependent manufacturer and one single permit supplier is concerned. A manufacturer is usually a member of a supply chain rather than an isolated individual, and then its production decision must correlatively depend on the decisions of other members (Li et al. 1996; Cachon 2003; Flapper et al. 2005; Linton et al. 2007; Benjaafar et al. 2009). In an emission-dependent supply chain, the emission permit supplier with self-interest lies on the upstream side of the emission-dependent manufacturer since emission permit becomes requisite of production. There is competitive and cooperative relationship between them. In such game process, the optimal decisions of the parties are made, and the systemwide efficiency of the supply chain is realized (Li et al. 1996; Cachon 2003; Cachon and Netessine 2006). Many traditional supply chain problems are formulated based on the newsvendor model, such as Taylor (2002); Cachon and Lariviere (2005) etc. Cachon (2003) suggested that the newsvendor model is not complex, but it is sufficiently rich to study supply chain coordination. Su (2008) also considered that the newsvendor model is an indispensable building block in the operations literature on supply chain coordination and contracting. In this view, the decision-makings of parties in an emission-dependent supply chain can be game-theoretically analyzed in the context of newsvendor without loss of generality. The paper, in the context of newsvendor, investigates the behavior and decision-making of each member. In their own self-interest, the emission permit supplier and the emission-dependent firm make their optimal decisions on permits pricing and production quantity respectively. To do so, a game-theoretical model will be proposed and the Nash equilibrium will be derived.

The rest of the paper is organized as follows. Section 2 gives the literature review of the emission-related theoretical or empirical researches. Section 3 sets forth the characteristics of the concerned issue, and narrates relevant assumptions and notations of this paper. In Sect. 4 we will develop game-theoretical model of two parties of the emission-dependent supply chain. In their own self-interest, the emission permit supplier and the emission-dependent firm make their optimal decisions on permits pricing and production quantity respectively. The Nash equilibrium will be derived finally. Section 5 will give a numerical example and make sensitivity analysis to show the application of the model. Several valuable managerial insights are presented as well. Finally, concluding remark and future research are given in Sect. 6.

## 2 Literature review

Most emission-related theoretical or empirical researches have focused on macro issues of emission permits and trading, such as environmental policy, international trade of emission permits, etc.

Decades before UNFCCC was sanctioned, Montgomery (1972) and Tietenberg (1985) had conceptually proposed prospective ideas on emissions trading. Ellerman et al. (1998) considered three basic cases including no trading, Annex II trading and full global trading, and further disclosed the advantage of emissions trading under the Kyoto Protocol with marginal abatement curves (MACs) which represent the marginal cost of reducing carbon emissions by different amounts within an economy. Ellerman et al. (2007) compared the total costs of implementing the Kyoto Protocol for Annex II countries with and without emission trading. The result showed that emission trading made the cost to achieve the purpose of emissions reduction 50% less than that in the case of no trading. By evaluating the efficacy of international trade in carbon emission permits between non-cooperative countries, Carbone et al. (2009) founded that emission trade agreements are still effective when countries are guided strictly by their national self-interest, and smaller groupings pairing developing and developed-world partners often perform better than agreements with larger rosters.

The effects of emission taxation or trading schemes on the industry or national economic interest are investigated in some papers. Jaffe et al. (1995) disclosed the linkage between environmental regulation and international competitiveness and showed that environmental regulations have no large adverse effects on competitiveness. Böhringer (2002) investigated how restrictions for emission trading to the energy-intensive power sector would affect the magnitude and distribution of abatement costs across EU countries vis-à-vis a comprehensive EU emission trading regime. It is found that trade restrictions may create a more unequal distribution of abatement costs across member states than is the case for a comprehensive trade regime. Monica and Frabcesco (2007) analyzed the impact of trading of $CO_2$ emissions allowances on electricity pricing under the European Emissions Trading Scheme (ETS), and compared the impact of ETS under market power and perfect competition environment. Kara et al. (2008) discussed the impact of EU $CO_2$ emissions trading on electricity markets and electricity consumers in Finland. Damien and Philippe (2008) quantified the impact of the European Emission Trading Scheme (ETS) on the two dimensions of competitiveness—production and profitability—for the iron and steel industry. Fodha and Zaghdoud (2010) investigated the relationship between economic growth and pollutant emissions for a small and open developing country, Tunisia. The authors used carbon dioxide ($CO_2$) and sulfur dioxide ($SO_2$) as the environmental indicators, and GDP as the economic indicator. This paper found that there is a long-run cointegrating relationship between the per capita emissions of two pollutants and the per capita GDP. This implies that an emission reduction policies and more investment in pollution abatement expense will not hurt economic growth. Oder and Rentz (1994) developed a energy-emission model to allow for fuzzy parameters. a fuzzy linear program is developed, which has been applied to an energy-emission model of Lithuania. The application for Lithuania shows that budget restrictions interfere with the aim of considerably reducing $SO_2$ and $NO_x$ emissions in the coming decades.

Some literatures study bilateral trading rules in emission permits among economic entities as well as their corresponding unilateral regulation. Burtraw et al. (1998) studied the bilateral trade in emissions of sulfur dioxide and presented the results of an integrated assessment of the benefits and costs of reduction in emissions of sulfur dioxide. Rehdanz and Tol (2005) used a two-country model to analyze the corresponding unilateral regulation under bilateral trade in greenhouse gas emission permits. Bernard et al. (2008) proposed a computable dynamic game model of the strategic competition between Russia and developing countries (DCs), mainly represented by China, on the international market of emission permits created by the Kyoto Protocol. Furthermore, the competitive scenario was compared with a monopoly situation where only Russia is allowed to play strategically. The impact of allowing DCs to intervene on the international emission trading market is thus assessed. Weikard and Dellink (2010) examined renegotiations of international climate agreements for carbon abatement. They explore coalition stability under ‘optimal transfers’ that have been suggested to stabilize international environmental agreements.

The aforementioned literatures suggest that most theoretical and empirical research have almost focused on macro-aspects of emission permits and trading, but little attention is given to micro-aspects of emission trading. It is believed that operational research with emission trading is also significant. Bode (2006) analyzed different emission permit allocation option in multi-period emissions trading in electricity sector. Kleindorfer et al. (2005) proposed the concept named sustainable operations management. Linton et al. (2007) then introduced the "sustainable supply chain", and provided a background to better understand current trends in operations management research. Corbett and Klassen (2006) discussed that environmentally sustainable mechanism and its application in both theory and practice of operations management. The paper illustrated that lean is not green through two principal areas of lean operations—quality management and supply chain management. Kleindorfer et al. (2005), Corbett and Klassen (2006) and Linton et al. (2007) reviewed the literature on sustainability and production operation. However, the concern in that literature tends to be more focused on product recycling and reuse (e.g., Flapper et al. 2005; Venkat and Wakeland 2006). There are also some economics literatures focused on the design of emission markets (e.g., Laffont and Tirole 1996a, 1996b, etc.). Benjaafar et al. (2009) found that an extensive search in the journals (such as Management Science, Operations Research, Manufacturing and Service Operations Management, etc.) published by INFORMS did not yield any papers dealing directly with the issue of carbon emissions and operations. In addition, the paper explored how carbon emission concerns could be integrated into operational decision-making.

## 3 Problem characteristics, notations and assumptions

This paper focuses on the impact of emission 'cap-and-trade' mechanism in an emission-dependent supply chain in the context of newsvendor. A typical two-stage system with one single emission-dependent manufacturer and one single permit supplier is concerned; the manufacturer faces stochastic demand for product; single period is considered, which implies that the product as well as the emission permit cannot be transferred from one period to another with zero residual value assumed. For the purpose of simplification, return of the unused permit is not allowed, and costs associated with inventory and shortage are neglected to focalize the problem on emission factor. Moreover, full rationality and complete information are assumed.

The permit supplier 'produces' emission permits, and the supply cost per unit permit is assumed to be $c_e$. In his own self-interest, the permit supplier makes the optimal pricing decision. The notation $w_e$ is used to denote the selling price per unit permit, $w_e > c_e$.

The emission-dependent manufacturer has to decide the total production quantity $q$ according to the market demand of his product in the selling season, denoted by $x$. Stochastic demand is considered, therefore the manufacturer cannot know the demand exactly in advance but thinks it follows a distribution with probability density function $f(\cdot)$ and cumulative distribution function $F(\cdot)$ via marketing analysis. It is clear that emission was directly proportional to production in a certain technical condition, i.e., the more the manufacturer produces, the more emission will be emitted. Here, $e$ units of emission per unit product are assumed, thus the total emission for $q$ units of products must be $eq$. The government allocates an emission quota/cap for the selling season, denoted by $C_g$, to the emission-dependent manufacturer. If the cap is insufficient to satisfy the target production, $e_t$ units of extra permit should be purchased at the price of $w_e$ from the permit supplier, i.e. $e_t = (eq - C_g)^+$.

Some other parameters involved are given as follows:

$\mu$: Expected demand for the final products, $\mu \equiv \int_0^\infty x f(x) dx$;
$p$ : The selling price of final products;

| | |
|---|---|
| $c$: | Unit production cost; |
| $\Pi_M, \pi_M$: | The manufacturer's net profit and its expectation. |

## 4 Analytical model

In this section, we will explore the decision-making of two parties of the emission-dependent supply chain. A game-theoretical model is developed and the game process is described. In the game process, the emission permit supplier and the emission-dependent firm, in pursuit of their own maximal profits, make their optimal decisions on permits pricing and production quantity respectively. The systemwide efficiency of the supply chain is realized finally.

### 4.1 The decision-making of emission-dependent manufacturer

Since shortage and inventory costs are not considered for simplification and focalization, the expenses that the emission-dependent manufacturer incurs must include the production cost and permit procurement cost. Then, its net profit can be given by

$$\Pi_M = p(x \wedge q) - cq - w_e e_t \tag{1}$$

Under the general assumption that the market demand for the final products is realized stochastically and follows a distribution with probability density function (p.d.f.) $f(\cdot)$ and cumulative distribution function (c.d.f.) $F(\cdot)$, the manufacturer's expected profit is formulated as

$$\pi_M = pS(q) - cq - w_e e_t \tag{2}$$

where $S(q)$ denotes expected sales when the manufacturer decides the production of $q$, $S(q) \equiv E(x \wedge q) = \int_0^q \bar{F}(x)dx$, $\bar{F}(\cdot) \equiv 1 - F(\cdot)$. Recalling that $e_t = (eq - C_g)^+$, we have

$$\pi_M = \begin{cases} pS(q) - cq, & \text{if } q \le C_g/e; \\ pS(q) - cq - w_e(eq - C_g), & \text{if } q \ge C_g/e. \end{cases} \tag{3}$$

For simplification, $L$ and $U$ are introduced to represent the intervals $[0, C_g/e]$ and $[C_g/e, +\infty]$ respectively. It is clear that the expected profit function is piecewise concave with respect to the production. However, (3) yields unique second derivative as follows regardless of $L$ or $U$.

$$\frac{\partial^2 \pi_M}{\partial q^2} = -pf(q) < 0 \tag{4}$$

Two cases (Intervals $L$ and $U$) should be discussed respectively and three valuable propositions will be proposed as follows.

**Proposition 1** *If the production decision is made in the interval $L = [0, C_g/e]$, the optimal production to maximize the profit of the manufacturer can be given by*

$$q_L^* = \min\left\{\frac{C_g}{e}, F^{-1}\left(\frac{p-c}{p}\right)\right\} \tag{5}$$

*Proof* In this case, the expected profit function of the manufacturer, restated as $\pi_M^L = pS(q) - cq, q \in L$, is boundedly concave, which insures the existence and uniqueness of the optimal production, either at the first-order stationary point ($SP_L$ for short) or at the boundaries of the interval $L$. The first-order partial derivative of $\pi_M^L$ with respect to $q$ should be

$$\frac{\partial \pi_M^L}{\partial q} = p\bar{F}(q) - c$$

Accordingly,

$$SP_L = F^{-1}\left(\frac{p-c}{p}\right) \tag{6}$$

$$\lim_{q \to 0^+} \frac{\partial \pi_M^L}{\partial q} = p - c > 0 \tag{7}$$

Equation (7) means that $\pi_M^L$ is monotonically increasing with respect to $q$ when $q$ is small enough. Then the lower boundary $q = 0$ is not the optimal. Therefore, if production decision is made in the interval $L$, the optimal production must be determined at the first-order stationary point $SP_L$ or upper boundary of the interval $L$ by regarding whether the first-order stationary point belongs to the interval $L$. Then we have $q_L^* = \min\{C_g/e, SP_L\}$. □

**Proposition 2** *If the production decision is made in the interval* $U = [C_g/e, +\infty)$, *the optimal production to maximize the profit of the manufacturer can be given by*

$$q_U^* = \max\left\{\frac{C_g}{e}, F^{-1}\left(\frac{p-c-w_e e}{p}\right)\right\} \tag{8}$$

*Proof* In this case, the expected profit function of the manufacturer is formulated as $\pi_M^U = pS(q) - cq - w_e(eq - C_g), q \in U$, which is a lower bounded concave function regarding $q$. Therefore, the unique optimal production must be obtained at the first-order stationary point or at the lower boundary of the interval $U$ by regarding whether the first-order stationary point belongs to the interval $U$. The first-order condition $\partial \pi_M^U / \partial q = p\bar{F}(q) - c - w_e e = 0$ yields the first-order stationary point ($SP_U$ for short) as follows.

$$SP_U(w_e) = F^{-1}\left(\frac{p-c-w_e e}{p}\right) \tag{9}$$

Note that $SP_U$ is a decreasing function with respect to the decision variable $w_e$. Accordingly, the optimal production quantity can be given by $q_U^* = \max\{C_g/e, SP_U(w_e)\}$. □

**Proposition 3** *When the selling price of final products, unit production cost and emission per unit product are assumed to be exogenous, the globally optimal production quantity of the manufacturer* $q^*$ *must depend jointly on its emission cap from the government* $C_g$ *and the price per unit permit determined by the permit supplier* $w_e$ *as follows.*

$$q^*(w_e, C_g) = \begin{cases} SP_U(w_e), & \text{if } C_g < e \cdot SP_U(w_e); \\ \frac{C_g}{e}, & \text{if } C_g \in [e \cdot SP_U(w_e), e \cdot SP_L]; \\ SP_L, & \text{if } C_g > e \cdot SP_L. \end{cases} \tag{10}$$

*Proof* Recalling that $SP_L = F^{-1}(\frac{p-c}{p})$, $SP_U(w_e) = F^{-1}(\frac{p-c-w_e e}{p})$. Since $\frac{p-c-w_e e}{p} < \frac{p-c}{p}$, we have $SP_U(w_e) < SP_L$. Note that $\frac{C_g}{e}$ belongs to the interval $L$ as well as the interval $U$.

(1) If $C_g < e \cdot SP_U(w_e)$, apparently we have $C_g < e \cdot SP_L$. Then it is known from Propositions 1 and 2 that

$$q_L^* = \frac{C_g}{e}; \qquad q_U^* = SP_U(w_e)$$

Comparing the manufacturer's expected profits where $q = q_L^*$ and $q = q_U^*$, the one that results in the larger profit must be the globally optimal production. Since the optimal production in the interval $U$ is $q_U^* = SP_U(w_e)$, while $q_L^* = C_g/e \in U$, therefore the globally optimal production must be $q^* = SP_U(w_e)$.

(2) If $C_g > e \cdot SP_L$, accordingly $C_g > e \cdot SP_U(w_e)$. According to Propositions 1 and 2, we have

$$q_L^* = SP_L; \qquad q_U^* = \frac{C_g}{e}$$

Similarly, the optimal production in the interval $L$ is $q_L^* = SP_L$ while $q_U^* = C_g/e \in L$, and then the globally optimal production must be $q^* = SP_L$.

(3) If $C_g \in [e \cdot SP_U(w_e), e \cdot SP_L]$, Propositions 1 and 2 yield that $q_L^* = q_U^* = C_g/e$, therefore, $q^* = C_g/e$ is certain to be globally optimal. □

As mentioned above, two major sources of emission permit are considered—emission cap imposed by the government, and permits purchased via emission trading. To meet the target optimal production, it may be necessary for the manufacturer to purchase extra permit from the upstream permit supplier. The notation $e_t^*$ is employed to denote the ordering volume of the permit with respect to the optimal production $q^*$, i.e. $e_t^* = (eq^* - C_g)^+$. In consideration that the optimal production is made according to (10), $C_g < e \cdot SP_U w_e)$ yields $q^* = SP_U(w_e)$, which implies that the emission cap is insufficient to satisfy the optimal production, $e \cdot SP_U(w_e) - C_g$ units of permit should be ordered; If $C_g \in [e \cdot SP_U(w_e), e \cdot SP_L]$, we have $q^* = C_g/e$, then the imposed cap is just enough, $e_t^* = 0$; For the case $C_g > e \cdot SP_L$, the optimal production must be $q^* = SP_L$, therefore the cap is surplus for production, $e_t^* = 0$. Consequently, it can be concluded that, whether extra permit is needed depends on the numerical relationship between $C_g$ and $e \cdot SP_U(w_e)$, while independent of $SP_L$, i.e. the ordering volume of permit in the aforementioned cases can be uniformly given as follows.

$$e_t^*(w_e, C_g) = \left[e \cdot SP_U(w_e) - C_g\right]^+ = \left[eF^{-1}\left(\frac{p-c-w_e e}{p}\right) - C_g\right]^+ \tag{11}$$

### 4.2 The decision-making of permit supplier

As mentioned above, if the emission cap imposed by the government is insufficient to meet the target production, the emission-dependent manufacturer may purchase $e_t^*(w_e, C_g)$ units of permit from the permit supplier. Therefore, the supplier's net profit can be given by

$$\pi_S = (w_e - c_e)e_t^*(w_e, C_g) \tag{12}$$

Since full rationality and complete information are assumed, the permits supplier knows the manufacturer's reaction to its pricing decision of permit, which can be formulated by (10), i.e. the response function. Accordingly, it can also learn how its pricing decision affects its own final profit. That is, it knows (12). This process is essentially a typical Stackelberg game. The permit supplier, as the leader, moves first and decides the optimal price of emission permit. Then the emission-dependent manufacturer, as the follower, moves sequentially after observes the pricing decision of the permit supplier, will decide whether to accept the pricing or not and make its optimal production decision.

Considering that $e_t^*(w_e, C_g)$ is a piecewise function, let's make an analysis as follows.

If $C_g \geq e \cdot SP_U(w_e)$ or equivalently $w_e \geq \bar{w} \equiv [p\bar{F}(c_g/e) - c]/e$ ($\bar{w}$ is newly introduced for simplification), it is known from (11) that $e_t^*(w_e, C_g) = 0$. It implies that the manufacturer thinks the price of permit is too high by balancing a trade-off between its expected profit and the ordering cost of permit. In this case, the manufacturer will control the production scale according to the emission cap imposed by the government, and therefore the permit supplier cannot make profit. The rational permit supplier, in its own self-interest, must lower the permit price less than $\bar{w}$ in order to motivate the manufacturer's purchase behavior, $w_e \in (c_e, \bar{w})$. In this sense, $\bar{w}$ is endowed with a clear managerial implication—the upper limit of the profitable price for the permit supplier. We may as well name $(c_e, \bar{w})$ as the *profitably pricing interval*. That is to say, the permit supplier must make its pricing decision in the profitably pricing interval, which ensures that $C_g < e \cdot SP_U(w_e)$. Therefore, (11) can be restated as follows.

$$e_t^*(w_e, C_g) = e \cdot SP_U(w_e) - C_g, \quad w_e \in (c_e, \bar{w}) \tag{13}$$

**Proposition 4** *Taking into account the manufacturer's response, the unique optimal price of emission permit to maximize the profit of the permit supplier is given by* $w_e^* = V^{-1}(c_e)$, *where* $V^{-1}(\cdot)$ *is introduced to denote the inverse for the function* $V(\cdot)$ *defined as follows.*

$$V(w_e) \equiv w_e - \frac{p \cdot f(SP_U(w_e))}{e^2}[e \cdot SP_U(w_e) - C_g] \tag{14}$$

*Proof* For the purpose of profit maximization, the permit supplier can make its optimal pricing decision by solving the programming problem as follows.

$$\begin{aligned} \max_{w_e} \pi_S &= (w_e - c_e)e_t^*(w_e, C_g) \\ &= (w_e - c_e)[e \cdot SP_U(w_e) - C_g] \\ \text{s.t.} \quad & w_e \in (c_e, \bar{w}) \end{aligned} \tag{15}$$

To further investigate some properties of the profit function of the permit supplier, it is necessary to analyze the first-order partial derivative of the manufacturer's optimal quantity $q^*$ with respect to the permit price $w_e$ in the profitably pricing interval. Since $w_e \in (c_e, \bar{w})$ yields $c_g < e \cdot SP_U(w_e)$, it's known from (10) that $q^* = SP_U(w_e)$. Recalling (9), we have

$$F(SP_U(w_e)) = \frac{p - c - w_e e}{p}$$

Then, the first-order condition of $F(SP_U(w_e))$ regarding $w_e$ should be

$$\frac{\partial F(SP_U(w_e))}{\partial w_e} = -\frac{e}{p}$$

For the nested function $F(SP_U(w_e))$, it is known that

$$\frac{\partial F(SP_U(w_e))}{\partial w_e} = \frac{\partial F(SP_U(w_e))}{\partial SP_U(w_e)} \cdot \frac{\partial SP_U(w_e)}{\partial w_e}$$

Accordingly,

$$\frac{\partial SP_U(w_e)}{\partial w_e}=\frac{\partial F(SP_U(w_e))}{\partial w_e}\bigg/\frac{\partial F(SP_U(w_e))}{\partial SP_U(w_e)}=-\frac{e}{pf(SP_U)}$$

Hereby, we can further analyze the relationship between the profit of the permit supplier and its pricing decision. Recalling the programming problem (15), the first-order condition and the second-order derivative of $\pi_s$ regarding $w_e$ should be

$$\begin{aligned}\frac{\partial \pi_S}{\partial w_e}&=e\cdot SP_U(w_e)-C_g+e(w_e-c_e)\frac{\partial SP_U(w_e)}{\partial w_e}\\&=e\cdot SP_U(w_e)-C_g-\frac{e^2(w_e-c_e)}{pf(SP_U(w_e))}=0\end{aligned}\tag{16}$$

$$\frac{\partial^2\pi_S}{\partial w_e^2}=-\frac{e^2}{pf(SP_U)}\left(2+\frac{e(w_e-c_e)f'(SP_U)}{p[f(SP_U)]^2}\right)\tag{17}$$

To discuss the unimodality of $\pi_s$ regarding $w_e$, it is necessary to introduce the concept of *increasing failure rate* (IFR) and *decreasing failure rate* (DFR) (Barlow and Proschan 1965; Brusset 2009; Lariviere 2006; Lariviere and Porteus 2001). For a probability distribution with p.d.f. $f(\cdot)$ and c.d.f. $F(\cdot)$, its failure rate function is defined as $r(\cdot)\equiv f(\cdot)/\bar{F}(\cdot)$ where $\bar{F}(\cdot)\equiv 1-F(\cdot)$. Distributions with increasing/decreasing failure rates in their probability spaces are called IFR/DFR distributions. Fortunately, most widely applied demand distributions are IFR, such as the normal, the power, the extreme value, the Weibull with shape parameter greater than 1 and the gamma with shape parameter greater than 1 etc. As a special case, the negative exponential distributions have constant failure rates, which do not meet IFR. Nevertheless, in order to take such distributions into account, increasing and constant failure rates are uniformly called *Monotonically Non-Decreasing Failure Rate* (MNDFR) hereafter, i.e. $r'(\cdot)\geq 0$. The aforementioned distributions are abundant enough to fit random demands in practice. In many well-known supply chain related literatures, such as Cachon (2003), Lariviere and Lariviere and Porteus (2001) etc., IFR or its extension IGFR (*increasing generalized failure rate*) is introduced to study supply chain with stochastic demand. In this paper, the market demand of the final product is considered to be MNDFR, therefore we have

$$r'(x)=\frac{f'(x)\bar{F}(x)+[f(x)]^2}{[\bar{F}(x)]^2}\geq 0$$

Equivalently,

$$\frac{f'(x)}{[f(x)]^2}\geq-\frac{1}{\bar{F}(x)}$$

It is clear that $c+w_e e>e(w_e-c_e)$, then for $x=SP_U(w_e)$, we have

$$\frac{f'(SP_U)}{[f(SP_U)]^2}\geq-\frac{1}{\bar{F}(SP_U)}=-\frac{p}{c+w_e e}>-\frac{p}{e(w_e-c_e)}>-\frac{2p}{e(w_e-c_e)}\tag{18}$$

Substituting (18) into (17) yields $\partial^2\pi_S/\partial w_e^2<0$, which ensures the strict concavity of $\pi_S$ with respect to $w_e$. Moreover, the first-order derivatives of $\pi_S$ with respect to $w_e$ at the upper and lower boundaries of the profitably pricing interval satisfy that

$$\left.\frac{\partial \pi_S}{\partial w_e}\right|_{w_e=c_e} = e\cdot SP_U(c_e) - C_g > 0; \qquad \left.\frac{\partial \pi_S}{\partial w_e}\right|_{w_e=\bar{w}} = -\frac{e^2(\bar{w}-c_e)}{pf(C_g/e)} < 0.$$

Therefore, the first-order stationary point is certain to be a member of the profitably pricing interval $(c_e, \bar{w})$ in view of the mean value theorem. Then (16) must yield the unique globally optimal pricing decision $w_e^* = V^{-1}(c_e)$, where $V(w_e^*) = w_e^* - p \cdot f(SP_U(w_e^*))[e \cdot SP_U(w_e^*) - C_g]/e^2 = c_e$, and a positive maximal profit for the permit supplier will be achieved. □

### 4.3 Game process and profit analysis

In this section, we will further discuss the profit levels of both parties and the overall supply chain. The game process of the emission-dependent manufacturer and the permit supplier can be concluded as follows.

(1) The permit supplier moves first to decide the optimal price of emission permit. With complete information, it knows the response of the emission-dependent manufacturer to the permit price (see (10)). Therefore, the optimal pricing decision will be made as $w_e^* = V^{-1}(c_e) \in (c_e, \bar{w})$, where

$$\bar{w} \equiv \frac{p\bar{F}(C_g/e) - c}{e}; \qquad SP_U(w_e) \equiv F^{-1}\left(\frac{p-c-w_e e}{p}\right);$$

$$V(w_e) \equiv w_e - \frac{pf(SP_U(w_e))}{e^2}[e \cdot SP_U(w_e) - C_g].$$

(2) The emission-dependent manufacturer, who moves sequentially after observes the pricing decision of the permit supplier, will accept and respond to this price in accordance with (10), and make its optimal production decision. Since $w_e^* = V^{-1}(c_e) \in (c_e, \bar{w})$ yields $C_g < e \cdot SP_U(w_e^*)$, the manufacturer makes the optimal production decision based on (10) as follows.

$$q^* = SP_U(w_e^*) = F^{-1}\left(\frac{p-c-eV^{-1}(c_e)}{p}\right)$$

Accordingly, the emission cap imposed by the government is insufficient to meet the target production, and therefore extra emission permit should be purchased from the permit supplier as follows.

$$e_t^* = eq^* - C_g = eF^{-1}\left(\frac{p-c-eV^{-1}(c_e)}{p}\right) - C_g$$

$(w_e^*, q^*)$ is the unique Nash equilibrium of the Stackelberg game where each player would not deviate unilaterally in its own self-interest. Then, the expected profit of both parties as well as the overall supply chain at the Nash equilibrium point can be given respectively as follows.

$$\begin{aligned}
\pi_S &= (w_e^* - c_e)(eq^* - C_g)\\
\pi_M &= pS(q^*) - cq^* - (eq^* - C_g)w_e^*\\
\pi &= pS(q^*) - (c + c_e e)q^* + c_e C_g
\end{aligned}$$

## 5 Numerical example and sensitivity analysis

In this section, we present a typical numerical analysis to corroborate and supplement the previous developments. Without loss of generality, the market demand for the final product is assumed to follow a left-truncated normal distribution. Definitely, let $x \equiv \max\{\tilde{x}, 0\}$, where $\tilde{x}$ is assumed normally distributed with mean of 150 and standard deviation of 10, i.e. $\tilde{x} \sim N(150, 10^2)$. By means of MATHEMATICA, it is easy to know that $Prob(\tilde{x} < 0) = 3.67110^{-51}$ is tiny enough to be neglected, and the probability density of $x$ is fairly close to that of $\tilde{x}$. Therefore, $\tilde{x}$ can be used to approximate $x$ for convenience of calculation.

Besides, let the emission cap allocated to the emission-dependent manufacturer by the government $C_g = 100$. The selling price of the final products, the unit production cost, the supply cost per unit permit and the emission per unit product are assumed $p = 150$, $c = 8$, $c_e = 5$, $e = 1.5$ respectively.

In such settings, by fully taking the manufacturer's response into account, the permit supplier moves first to decide the optimal price of the emission permit, which could be derived according to Proposition 4 as $w_e^* = V^{-1}(5) = 88.433$. Observing this pricing decision, the manufacturer moves sequentially in response according to (10), therefore the optimal production $q^* = 134.646$ is yielded. In this production level, the emission cap from the government is insufficient; $e_t^* = 101.968$ units of permit should be purchased from the permit supplier. As a result, the expected profits of both parties are maximized, i.e., $\pi_S = 8507.517$ and $\pi_M = 10061.777$, and the profit of the overall supply chain $\pi = 18569.294$ is realized accordingly.

In order to make a further study about the influence of several exogenous parameters, including the emission cap $C_g$ and standard deviation $\sigma$, on the decision-makings as well as the optimal results, we make sensitivity analysis and come to several valuable managerial insights into the environmental policy and the market risk as follows.

In case the emission cap allocated by government reduces to $C_g = 50$ and the base values of the others are maintained, the optimal permit price for the permit supplier would increase to $w_e^* = 90.655$ and the optimal production for the emission-dependent manufacturer decrease to $q^* = 132.506$ respectively. The manufacturer must purchase $e_t^* = 148.759$ units of permit. The expected profits of both parties and the overall system change to $\pi_S = 12742.037$, $\pi_M = 5305.740$ and $\pi = 18047.777$. It means that, if the government adopts stricter environmental protection policy (or referred to as *tight environmental policy*), the bargaining power of the manufacturer will be weakened, while the permit supplier will have a stronger pricing power and benefit from the tight environmental policy. The profitability of the overall supply chain falls slightly. In the macroeconomic considerations, the conclusion can be restated as: The government can sacrifice relatively less economic growth in exchange for significant environmental improvement by tightening environmental policy to make the green organizations and low-carbon industries benefit. The sensitivity of optimal results to emission cap is shown in Fig. 1.

The standard deviation of the demand distribution is a measure of the market volatility. The larger the dispersion or variability is, the higher the standard deviation. It is positively correlated to the market risk faced by the manufacturer. If the market volatility increases to $\sigma = 15$ and the base values of the other parameters are maintained, the optimal permit price for the permit supplier and the optimal production for the emission-dependent manufacturer would decrease to $w_e^* = 84.039$ and $q^* = 131.301$ respectively. $e_t^* = 96.952$ units of permit should be purchased to meet the production. The expected profits of both parties and the overall system change to $\pi_S = 7662.994$, $\pi_M = 10382.386$ and $\pi = 18045.380$. The managerial implication is clear. If solely taking more market risk, the manufacturer, for the

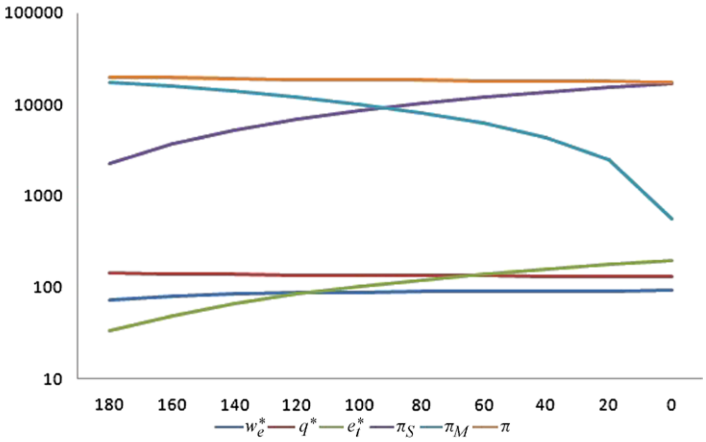

**Fig. 1** Sensitivity of optimal results to emission cap

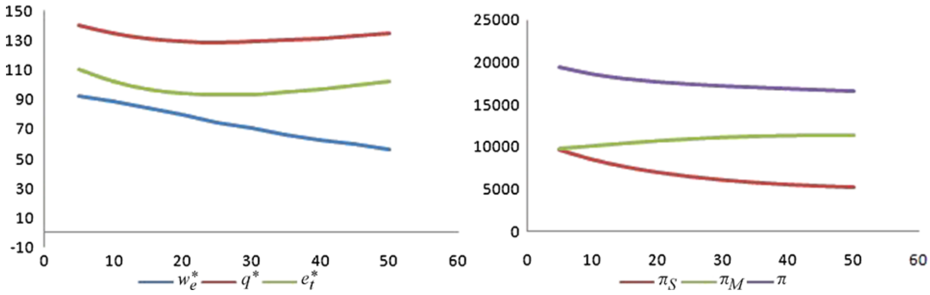

**Fig. 2** Sensitivity of optimal results to market volatility

profit maximization, will make the more cautious decision and control the production scale at a lower level. Therefore, considering the manufacturer's cautious decision and response to the permit pricing decision, the permit supplier, in its own self-interest, would share the market risk proactively by lowering the permit price to induce the manufacturer to expand production scale. The sensitivity of optimal results to market volatility is shown in Fig. 2.

## 6 Concluding remarks and future research

The paper studies the impact of the cap-and-trading mechanism on the decision-makings and system performance in a two-echelon emission-dependent supply chain, which consists of single emission-dependent manufacturer and single emission permit supplier. In pursuit of the maximal profit, the emission-dependent manufacturer decides the optimal production taking emission cap, market risk and the permit price into account. If the permit price decided by the permit supplier is too high to be accepted, the manufacturer will make a trade-off and control the production scale at a certain level that its on-hand emission permit (i.e., the imposed cap) can satisfy. As a result, no permit trading is needed, and therefore the permit supplier makes no profit. Since the permit supplier has complete information, he will decide the permit price in the profitably pricing interval in his own self-interest. The process is essentially a Stackelberg game. Both parties of the supply chain make the optimal decision to maximize their own profits. The emission permit supplier moves first to decide the optimal price of emission permit and then the emission-dependent manufacturer moves sequentially after observing the pricing decision of the permit supplier and decide the optimal production quantity. But the supplier should fully take into account the manufacturer's response to his pricing decision before he moves. Players' bargaining power in the game is affected by several exogenous factors, such as the governmental environment policy, the market risk, etc. Several managerial implications are concluded as follows by numerical example and sensitivity analysis. The government can sacrifice relatively less economic growth in exchange for significant environmental improvement by tightening environmental policy to make the green organizations and low-carbon industries benefit; when the market volatility becomes greater, the permit supplier, in its own self-interest, would share the market risk proactively by lowering the permit price to induce the manufacturer to expand production scale.

The paper makes an initial attempt to take the cap-and-trading mechanism into operations-related issues. There is still much room for further extensions and improvement, such as considering an emission-dependent supply chain with multiple periods, where the manufacturer might be allowed to transfer surplus permit over periods. Asymmetric information about the emission cap is worth investigating as well. When the emission cap is private information, the manufacturer may have motivation to inflate such information to the supplier to obtain more bargaining power. The permits supplier may be aware of this behavioral bias, and take corresponding action. Moreover, it seems valuable to consider how the government participates in the game and formulates the environmental policies to maximize the social welfare per unit permit.

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